電気材料技術雑誌　第11巻第２号
J. Soc. Elect. Mat. Eng.　Vol.11,　No.2　２００２

Electrically Tunable Waveguide Laser Based on a Dye-Doped Ferroelectric Liquid Crystal

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Laser action in a waveguide configuration has been demonstrated in a planar alignment cell of dye-doped chiral smectic liquid crystal mixtures with a short pitch helical structure. In this configuration, doped dye can effectively be excited by a pump beam illuminating perpendicularly the helical axis and the laser light emitted along the helical axis propagates in the waveguide. Lasing wavelength can be tuned by adjusting the periodicity of the helical pitch upon applying the electric field.

KEYWORDS：ferroelectric liquid crystal, photonic crystal, laser, stop band, waveguide

電界により発振波長制御可能な色素ドープ強誘電性液晶導波路レーザー

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色素をドープした螺旋ピッチの短いカイラルスメクチック液晶（強誘電性液晶）を用いたプラナー配向セルにおいて、導波路構造のレーザーを実現した。この構造においては、励起光が螺旋軸に対して平行に入射し、レーザー光は導波路中を螺旋軸に対して平行に伝搬するので、色素を効率よく励起できる。電界によって螺旋ピッチを制御することで発振波長を制御することができた。

1. Introduction

Photonic crystals having a three-dimensional ordered structure with a periodicity of optical wavelength have attracted considerable attention from both fundamental and practical points of view, because novel physical concepts such as photonic band gap have been theoretically predicted and various applications have been proposed[1-9]. Also in a one-dimensional periodic structure, the laser action has been expected at the photonic band edge where the photon group velocity approaches zero[10].

Liquid crystals including chiral molecules such as cholesteric and chiral smectic liquid crystals have self-organized helical structures. In such chiral liquid crystals with helical structure, the light propagating along the helical axis is selectively reflected depending on the polarization states (right-handed or left-handed) if the wavelength of the light matches to the optical pitch of the helical structure, which is a so-called selective reflection. Lasing at the band edge has been reported in the cholesteric[11-12], and chiral smectic[13-14] and polymeric cholesteric liquid crystals[15-16].

Chiral smectic liquid crystals with tilted structure show a ferroelectricity, which is called ferroelectric liquid crystal (FLC), and have an expected potential for the electrooptic applications because of the fast response to the electric field[17]. The helical structure of FLC can be easily deformed upon applying electric field and the helical pitch can be changed with a response time of the order of microsecond. Namely, the lasing wavelength can be expected to be controlled quickly upon the electric field.

Lasing in the liquid crystals has been performed in the cell configuration in which a helical axis is

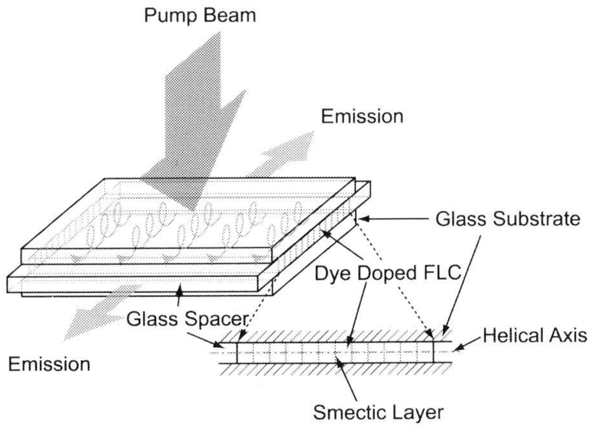

Fig.1. A cell configuration of waveguide laser. The waveguide laser output beam is emitted through a glass spacer.

図1　導波路レーザーにおけるセル構成。ガラスのスペーサーを通ってレーザーが出力される。

perpendicular to the substrates and laser light is emitted out perpendicularly to the cell surface. In this configuration, it is not easy to achieve alighment of high quality in a thick cell, so that it is difficult to extend an active region for the lasing. Moreover, a pump beam is absorbed in the vicinity of the interface between liquid crystal and substrate, and doped dye in a bulk is not effectively excited.

In this study, we design a planar cell configuration of dye-doped FLC for lasing and successfully demonstrate optically pumped lasing in a waveguide. In this waveguide liquid crystal laser, emission wavelength can be widely tuned by applying electric field.

2. Experiment

The FLC compound used in this study is a multi-component mixture having the chiral smectic C (SmC*) phase in a wide temperature range including a room temperature (~0°C to 68°C). A molecular tilt angle and spontaneous polarization at 30°C are 26° and 55nC/cm^2, respectively. As a laser dye doped in the FLC, a Coumarin 500 (Exciton) was used. The concentration of the dye is 0.2 wt%. The sample was filled into a sandwich cell, which consists of two glass plates. The cell configuration is shown in Fig1. In order to obtain a planar cell in which the helical axis is parallel to the glass substrates, surfaces of glass substrates were coated with polyimide (AL1254, Japan Synthetic Rubber) and were rubbed unidirectionally. Thin glass plates were used as spacers, whose thickness was about 150μm. In order to align the liquid crystal molecules perpendicularly to the spacers at the interfaces between the spacer and liquid crystal, and the edge of spacer glass was coated with polyimide (JALS-2021-R2, Japan Synthetic Rubber). The temperature of the sample cell was controlled using a hot bath and temperature controller. In order to apply an electric field normal to the helical axis, glass plates coated with an In-Sn oxide (ITO) were used as substrates.

As an excitation source, second harmonic light of a regenerative amplifier system based on a Ti:sapphire laser (Spectra Physics) was used. The pulse width, wavelength and pulse repetition frequency of the output laser beam were 150fs, 400nm and 1 kHz, respectively. The excitation energy can be varied within the range from 0.01 to 36 μJ/pulse using a neutral density filter. The excitation laser beam irradiated the sample perpendicularly to the cell plate and was rectangularly focused using two lenses to area of 0.3mm^2. The long axis of the irradiated area on the sample is parallel to the helical axis of the FLC. The emission along the helical axis passed through the spacer glass film and went outside the cell. The spectrum of the light emitted through the glass spacer was measured using a charge-coupled-device (CCD) multichannel photodetector (Hamamatsu Photonics, PMA-11) having spectral resolution of 3nm. For the measurement with a higher resolution, a spectrograph (Oriel MS257) with a CCD detector having spectral resolution of 0.3nm was used. The collecting direction was parallel to the cell surface, and the helical axis.

3. Results and Discussion

Figure 2 shows the emission spectra of the dye-doped FLC as a function of the excitation pulse energy at 22oC. For low excitation energy (<7.29 μJ/pulse), the spectrum is dominated by a broad spontaneous emission and the dip is observed in the broad spectrum. The wavelength of the dip shown in Fig.2 coincides with that of the stop band for the half pitch of the helix of FLC. This dip is wider than that of homeotropically aligned cell. As the excitation energy increases, the emission intensity is

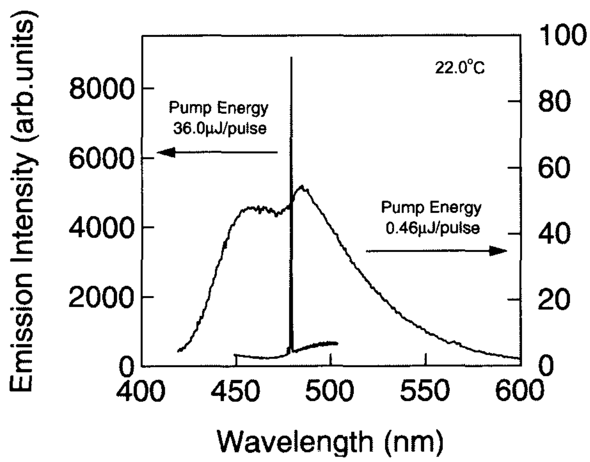

Fig.2. Emission spectra of a dye doped FLC as a function of pump pulse energy. A sharp emission peak appears at the edge of the stop band by the high-energy excitation (36μJ/pulse).

図２　発光スペクトルの励起光強度依存性。強励起(36μJ/pulse)時にストップバンド端において鋭い発光ピークが現れている。

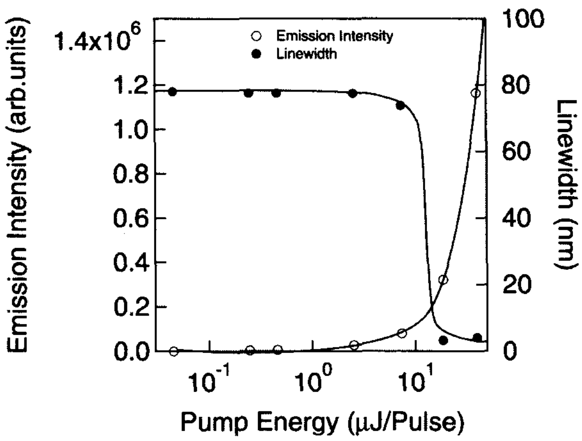

Fig.3. Pump Energy dependence of the peak intensity and linewidth (FWHM) of the emission spectra.

図3 発光ピーク強度および半値幅の励起光強度依存性

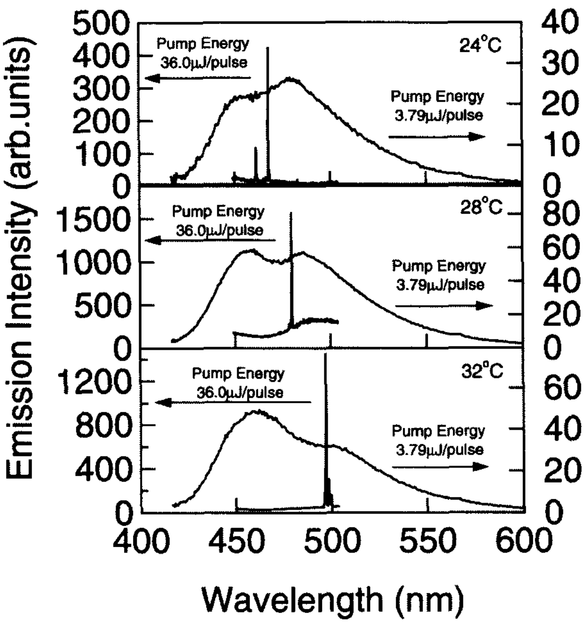

Fig.4. Temperature dependence of the emission spectra below and above threshold excitation energy for the lasing.

図4 閾値以下と閾値以上の励起光強度における発光スペクトルの温度依存性

enhanced. At high excitation energy (>18.6 μJ/pulse), a sharp emission peak appears at the edge of the dip. Although the full width at half maximum (FWHM) of the emission peak shown in Fig.2 is about 0.5nm, which is limited by the spectral resolution of our experimental setup.

The peak intensity and linewidth of the emission spectrum are shown in Fig.3 as a function of the pump pulse energy. This clearly indicates the presence of a lasing threshold. At lower excitation energy, the emission intensity is extremely low. Above the threshold at a pump pulse energy of about 10μJ/pulse, the emission intensity steeply increases. The linewidth of the emission spectrum also drastically decreases above the threshold. These results confirm that lasing occurs above the threshold of the pump energy at the edge of the photonic stop band in the spontaneous emission.

In order to confirm the contribution of the helix to the laser action, the temperature dependence of the emission spectrum was studied. Figure 4 shows emission spectra below and above the lasing threshold at various temperatures. The dip in spontaneous emission spectrum due to the stop band at low pump energy shifts with temperature, which corresponds to the change in the helical pitch of the host FLC. The helical pitch of FLC used in this study increases with increasing temperature. Therefore, the stop band shifts toward longer wavelength as the temperature increases.

As is evident from Fig.4, the lasing wavelength also shifts with temperature according to the shift of the stop band. This clearly indicates that the laser action in the waveguide is based on the periodic structure of the FLC helix.

The helical pitch of the FLC can be controlled also by the electric field, and the FLC should show a fast response of the molecular reorientation to the field because of a strong interaction between spontaneous polarization Ps and the electric field.

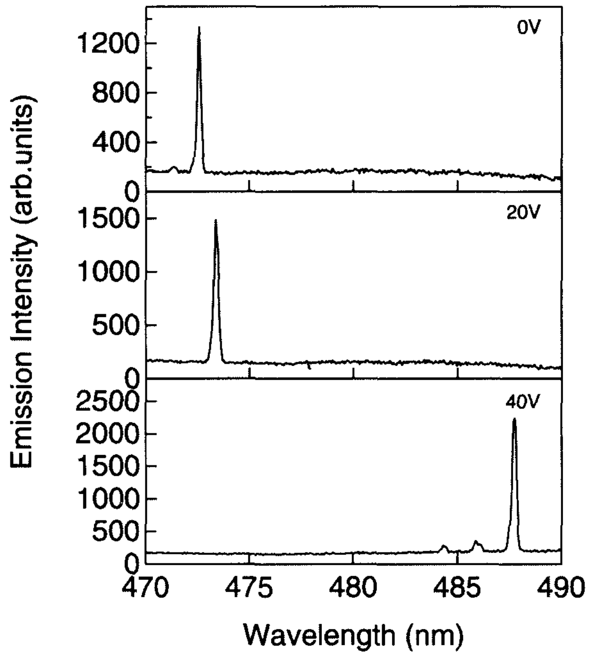

Fig.5. Laser emission spectra as a function of the voltage applied perpendicularly to the helical axis.
図5　レーザー発振スペクトルの電圧依存性

Figure 5 shows laser emission spectra as a function of the voltage applied perpendicularly to the helical axis. As is evident from the figure, the lasing wavelength shifts toward longer wavelength with increasing voltage. In spite of a low field (2.0 kV/cm), a wide tuning of the lasing wavelength was achieved.

Ps in FLC points normal to the molecules and parallel to the smectic layers. In the absence of the electric field, the helical structure is formed.

Namely, the long molecular axes of the FLC tilting with respect to the layer normal rotate around the layer normal (helical axis) from one layer to the next. In this structure, Ps of the molecules also rotates around the helical axis. When the electric field is applied parallel to the layer, i.e. perpendicular to the helical axis, Ps intends to point along the field direction and FLC molecules also orient to the direction normal to the field, resulting in the increase of the helical pitch. The helical pitch monotonously increases as the voltage increases below the critical voltage which completely unwounds the helical structure. The shift of the lasing wavelength shown in Fig.5 originates from the elongation of helical pitch caused by the field application. Therefore, a high-speed modulation of the laser action is expected using the dye-doped FLC.

4. Conclusions

In conclusions, optically pumped laser emission was observed at the edge of one-dimensional photonic band of dye-doped chiral smectic liquid crystal with a periodic spiral structure. Lasing wavelength was tuned by adjusting the period of the helical structure with temperature.

Acknowledgment

This work is supported by a Grant-in-Aid for Scientific Research from the Japan Ministry of Education, Culture, Sports, Science and Technology.

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(2002年10月15日受理)